COPING WITH ATMOSPHERIC TURBULENCE IN THE SELECTION OF LASER HARDENING TECHNOLOGY FOR FCS TARGETING SYSTEMS

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1. INTRODUCTION

The FCS Laser-Hardened Vision STO seeks to develop an electro-optic targeting vision system that utilizes a combination of nonlinear and sacrificial materials to provide protection from damage by frequency-agile battlefield lasers at both long and short range. Evidently, the selection of sensor protection technologies for incorporation into the final targeting system will be based on their optical limiting performance *under field conditions*. While few optical limiting devices perform as well in the field as in the laboratory, some, notably an otherwise extremely promising prototype sacrificial mirror, exhibit a discrepancy that is particularly striking. In the case of a thin, passive limiting component (*e.g.*, ablative mirror or dye cell) situated at a focal plane, the decrease in performance can be attributed to the randomly fluctuating axial displacement of the focal plane that is known to arise from the effects of atmospheric turbulence on a propagating laser beam. I present the results of a quantitative study of the effects of turbulence-induced focal shift on the performance of passive optical limiting devices. The results apply not only to the FCS targeting system, but to all laser eye and sensor protection devices that employ a thin, passive component whose optical limiting performance depends strongly on the input irradiance or the input fluence.

2. A SEMI-EMPIRICAL MODEL

Depending on the degree of collimation, the phase front of a Gaussian laser beam far from its source ranges from approximately planar (i.e., infinite radius of curvature) to very nearly spherical, with the radius of curvature equal to the propagation distance. Turbulence gives rise, among other things, to additional wave front curvature over and above that of a spherical wave [Belen'kii and Mironov, 1980]. Researchers in the United Kingdom recently measured the radii of curvature associated with this effect, obtaining values ranging from 180 m for very turbulent conditions through 250 m ("medium turbulence") to 500 m ("low turbulence") [Hollins et al., 1998]. A wave front with radius of curvature R displaces the focus of a lens of focal length $f \ll R$ a distance given approximately by f^2/R.

Detailed modeling studies were performed on a variety of passive optical limiting systems, both those employing an ablative mirror and those utilizing a cell or thin film of nonlinear material. Figure 1 shows the results for a 3.8-μm film of a newly developed pure liquid lead phthalocyanine [Flom et al., 1997; Pong et al., 1997]; these results are fairly typical.

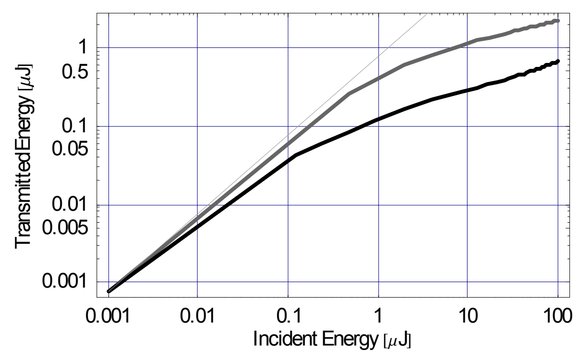

Fig. 1. Calculated *f*/12 optical limiting by a 3.8-μm film of PbPc(β-PEO)$_4$. Thick black curve: no turbulence. Thick gray curve: strong turbulence.

Turbulence had a negative impact on the optical limiting performance of all systems examined and was responsible, in the worst cases, for a four-fold increase in the energy exiting the limiter. Thin limiting devices were found to suffer a more severe degradation in performance than thick ones. However, even when their greater performance losses were taken into account, certain thin limiters employing nonlinear dyes still out-performed equivalent thick systems using lower concentrations of the same dyes.

3. IMPLICATIONS FOR SYSTEM DESIGN

3.1 Reduction in Aperture Size

The model shows that the turbulence-induced decrease in the irradiance reaching an optical limiting device situated in the focal plane of the unperturbed optical system depends only on the effective aperture of the system and is independent of the focal length of the lens. This suggests that the negative impact of turbulence on limiter performance can be mitigated by reducing the size of the aperture. Of course, in the vast majority of cases, mission requirements preclude any reduction in aperture size, and even in those cases in which aperture reduction is feasible,

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reducing the aperture size of a system increases the impact of another by-product of atmospheric turbulence, scintillation. Scintillation leads to a significant diminution in the beam quality of the laser threat. The concomitant reduction of the system's ability to focus the threat radiation into an optical limiter would partially offset the positive effect of the reduction in the turbulence-induced focal shift by the smaller aperture.

Still, it remains true that the smaller the effective aperture of an optical limiter, the less its performance will be diminished by the effects of turbulence-induced focal shift. A 20% intensity loss at the center of an image patch is generally regarded as acceptable [Born and Wolf, 1980]. If issues of beam quality are disregarded, this criterion would be met in an optical limiter whose input aperture diameter does not exceed $[2\lambda R]^{1/2}$. For a 532-nm laser threat propagating through a region of high turbulence, the critical diameter is only about 13 mm.

3.2 Thick versus Thin Limters

The fact that thick devices suffer a smaller *decrease* in performance in the presence of turbulence than do thin ones suggests that the impact of atmospheric turbulence might be minimized through the use of limiting devices that are sufficiently thick that the shifted focal plane remains within the limiter. To protect an *f*/1.7 system with an aperture 10 cm in diameter, for example, one would employ a dye cell that is at least 350 μm thick. Of course, the performance of a thick limiter is generally inferior to that of a thin limiter of the same linear transmittance, at least until the fluence reaches levels at which processes not considered in the model (*e.g.*, bubble formation, plasma generation, etc.) become important. In limiters based on nonlinear dyes, these intrinsic advantages often render a thin realization superior to an equivalent thick realization even in the presence of turbulence. In this case, design decisions must be based on detailed modeling of the nonlinear response of the particular dye under consideration.

3.3 Ablative Mirrors

The two ablative mirrors modeled in this study display threshold energies that are quite low; for this reason, they represent the state of the art for this optical limiting technology. Modeling results indicate that these thresholds increase by more than an order of magnitude in the presence of strong atmospheric turbulence. To compound the difficulty, these mirrors display optical limiting curves whose slopes are not nearly as small at high input energies as one might desire. Now, to accurately assess the level of laser damage protection afforded by a particular optical system, one must take into consideration all aspects of the system (including, for direct-view systems, the aperture formed by the pupil of the eye), not just the performance of the optical limiting component. Even in the absence of such a detailed study, however, it is difficult to imagine how an optical limiter based *solely* on a current state-of-the-art ablative mirror could adequately protect a large-aperture system from the anticipated threat under field conditions.

Even though it appears that an ablative mirror is by itself insufficient to protect a large-aperture system from laser damage, such a mirror *could* be successfully employed to extend the dynamic range of a second limiter in a tandem arrangement [Hernández et al., 2000]. Of course, to the extent that the second component relies on high irradiance levels or high fluence levels for high performance, the displacement of the focal plane resulting from turbulence will degrade the overall limiting performance of the tandem device, just as if the second component were employed alone.

3.4 Indirect-View Systems

The displacement of the focus from its original, unperturbed position in response to the effects of atmospheric turbulence leads, in general, to a *reduction* in the irradiance and fluence levels in the original focal plane. Thus, a sensor situated at the original focus and protected by an immediately adjacent limiting component will experience no loss of previously existing protection as a result of this reduction in fluence/irradiance, at least as long as the assumptions of the model (in particular, the use of ensemble-average irradiance profiles and the resulting neglect of the effects of scintillation "hot spots") remain valid. To be sure, the displacement of focus will result in some degradation of the image recorded by the sensor, but it carries no additional threat of damage.

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